To appear in: New Horizons in Globular Cluster Astronomy
ASP Conference Series, Vol. ???, 2003
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Correlations of Globular Cluster Properties: Their Interpretations and Uses

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Abstract. Correlations among the independently measured physical properties of globular clusters (GCs) can provide powerful tests for theoretical models and new insights into their dynamics, formation, and evolution. We review briefly some of the previous work, and present preliminary results from a comparative study of GC correlations in the Local Group galaxies. The results so far indicate that these diverse GC systems follow the same fundamental correlations, suggesting a commonality of formative and evolutionary processes which produce them.

1. Introduction

Understanding of the physics, formation, and evolution of any type of astronomical objects or systems, including globular clusters (GCs) as a family, must rest on a solid, quantitative empirical foundation. In the order of an increasing information content, the first step is a definition of characteristic values, e.g., a typical mass or luminosity or half-light radius, etc. The next step is a determination of distribution functions for various physical quantities, e.g., the luminosity function. Finally, most information can be obtained from non-trivial correlations of independently measured or derived quantities. Such correlations are products of some physical or evolutionary processes, and as such contain valuable clues towards the understanding of the objects in question.

In the context of globular clusters, previous studies include, e.g., Chernoff & Djorgovski (1989), Djorgovski (1991, 1995, 1996), Djorgovski & Meylan (1994), Bellazzini et al. (1996), Bellazzini (1998), McLaughlin (2000), and numerous papers by Sidney van den Bergh, e.g, van den Bergh (1996). For a comparison of GCs with other old stellar systems, see, e.g., Kormendy (1985) or Djorgovski (1993). On-line compilations of Galactic GC data useful for such studies include Harris (1996), [1] which is an updated superset of the data [2] presented in the First Ivan King Festschrift (eds. Djorgovski & Meylan 1993). Both are now well overdue for a major revision and updates, including Hipparcos-based distances, uniform IR photometry and reddenings derived from the 2MASS data, better core parameters from the HST-based surface photometry, etc.

Additional insights can be gained by comparing correlations of GC properties in GC systems of different galaxies. Currently, we are in practice limited to the galaxies of the Local Group. Previous studies include, e.g., Fusi Pecci et al. (1994), Djorgovski et al. (1997), Dubath & Grillmair (1997), Dubath et al. (1997), Meylan et al. (2001), Barmby et al. (2002), etc. In this paper we present preliminary results from a new study of dynamical correlations for GC systems in several Local Group galaxies.

2. Correlations for Galactic GCs: A Brief Overview

A generic expectation from the differences in corresponding dynamical time scales is that the evolution at the core radius scales would be much faster than at the half-light radius scales. The former then reflects mainly the evolution towards the core collapse (and any self-similar behavior before and after the core collapse), whereas the latter reflects more the initial conditions and a long-term evolution. Position of a GC in the Galactic potential modulates the evolutionary effect through the effect of dynamical shocks due to the disk and bulge passages, in the sense that clusters exposed to more frequent and stronger shocks evolve faster. This introduces a secondary dependence on the distance to the Galactic center and plane in many of the observed trends and correlations. All this was well documented in the references cited above, and at least the qualitative agreement between the observations and theory is striking.

In a simple core collapse picture, as $t \to t_c$ (time of the maximum collapse), the core radius $r_c \to 0$, the concentration parameter $c \to \infty$, the central density $\rho_0 \to \infty$, and the central surface brightness $I_0 \to \infty$, in a self-similar manner; see, e.g., Meylan & Heggie (1997) for a review and references. The observed cluster properties at the core scale are thus driven towards a (nearly) 1-parameter sequence corresponding to the relative dynamical time away from the core collapse

[1] http://physun.physics.mcmaster.ca/Globular.html

[2] http://www.astro.caltech.edu/~george/glob/data.html

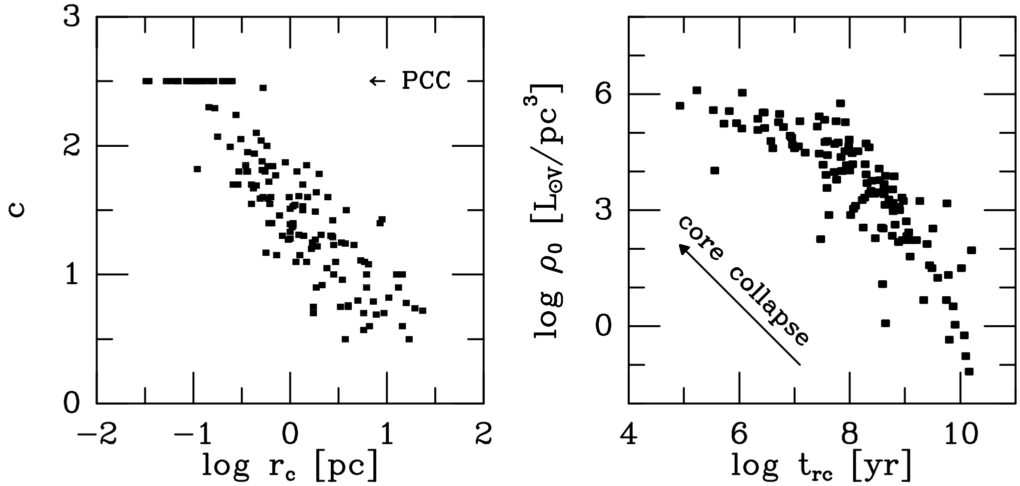

Figure 1. Examples of core parameter correlations, driven by the evolution towards the core collapse. *Left* : Correlation between two observables, the King concentration parameter c, and the core radius r_c. Clusters with an unresolved (from the ground) post-core-collapse (PCC) morphology have been assigned $c = 2.5$. *Right* : An illustrative correlation between two derived quantities, the central luminosity density, ρ_0, and the central relaxation time, t_{rc}.

(Fig. 1). This is indeed consistent with the observations: the predicted trend in simple single-component, Fokker-Planck core collapse models is $\rho_0 \sim {r_c}^{-2.23}$, whereas the observed trends are $I_0 \sim {r_c}^{-1.8\pm0.2}$ and $\rho_{0,lum} \sim {r_c}^{-2.6\pm0.2}$. This implies for the core mass $m_{core} \sim {r_c}^{0.3\pm0.2}(M/L)$, i.e., a nearly constant core mass, possibly slightly diminishing due to the evaporation of high-energy stars, and/or becoming slightly darker due to the mass segregation of heavy stellar remnants.

No such trends are seen at the half-light radius scale, where the dynamical range of the relaxation scales relative to the Galactic are is much smaller ($t_{rh} \sim 10^8 - 10^{10}$ yr, whereas at the core scale $t_{rc} \sim 10^5 - 10^{10}$ yr), so that the internal spread of GC properties dominates over the dynamical evolution effects.

Likewise, there are only a few noisy trends with the cluster luminosity ($\sim$ mass), which are apparent only when the data are binned: more luminous clusters tend to be more concentrated, $r_c \sim L^{-0.5\pm0.25}$, $\rho_0 \sim L^{2\pm1}$.

One can also estimate the rough tidal radii r_t from the observed surface brightness profiles, and the mean cluster densities ρ_t within the r_t. One finds a mean trend with the present Galactocentric radius R_{GC} of $r_t \sim R_{GC}^{0.37\pm0.05}$, as intuitively expected, and also $\rho_t \sim R_{GC}^{-1.6\pm0.2}$, close to the mean density law for the dark halo. Using a simple theory (Innanen et al. 1983) and an assumed Galactic rotation curve, it is then possible to estimate the perigalactic radii, R_{peri} (see Djorgovski 1986 for more details). Intriguingly, the ratio R_{GC}/R_{peri} peaks near the unity, with a long tail, suggesting that most GCs today are on nearly circular orbits. This could be a survival selection effect, or a reflection of the initial conditions, or a combination of the two.

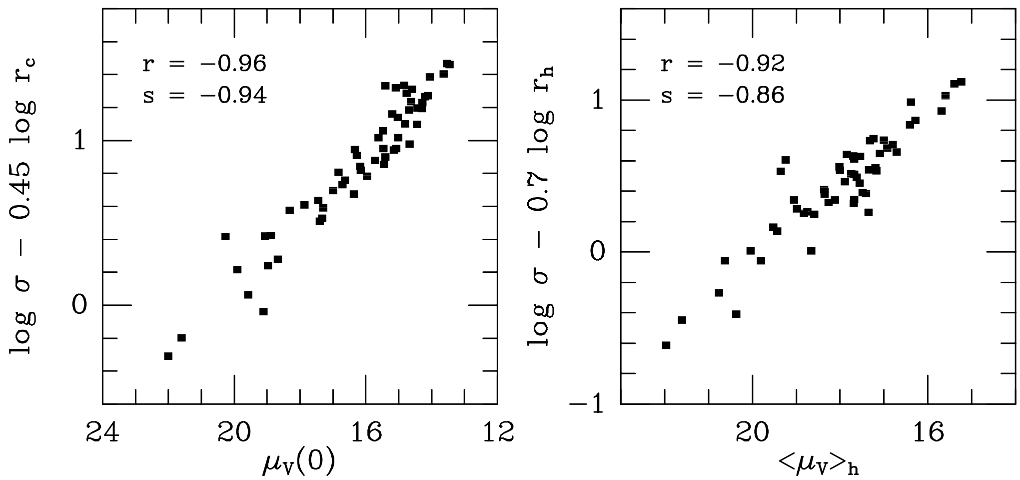

Figure 2. The Fundamental Plane (FP) bivariate correlations for GCs: an optimal combination of the central velocity dispersion (σ) and core radius (r_c) is correlated with the central surface brightness in the V band (left panel), and a different combination of σ and the half-light radius r_h with the mean surface brightness within r_h (right panel). Pearson (r) and Spearman (s) correlation coefficients are indicated in each panel. The residual scatter is completely accounted by the measurement errors.

Possibly the most interesting monovariate correlations are those including core velocity dispersions, σ: $\sigma \sim L^{0.6\pm0.15}$ (or equivalently, $L \sim \sigma^{5/3}$), $\sigma \sim I_0^{0.5\pm0.1}$, and $\sigma \sim I_h^{0.45\pm0.05}$, where I_h is the mean surface brightness within the half-light radius (see Figs. 3–4). The origin of these correlations is still not understood, but several possibilities exist; see, e.g., Djorgovski & Meylan (1994) for a discussion. These correlations may be reflecting the formative mechanisms of GCs, and they should be reproduced by any successful model of GC formation and long-term evolution. They are also very different from the corresponding correlations for elliptical and dwarf (dE, DSph) galaxies (Djorgovski 1993).

It is notable that GC metallicities do not seem to correlate with anything, in contrast to other old stellar systems. This strongly suggests that GCs were not self-enriched.

Another interesting question is how many independent physical parameters control the observable properties of GCs? Following the pioneering study by Brosche & Lentes (1984), more modern data sets suggest that there are at most 6 significant parameters among 9 or 10 independently measured observables (Djorgovski 1991, Djorgovski & Meylan 1994). If one considers just the observed photometric, structural, and dynamical parameters at both core and half-light scales, the statistical dimensionality of the data is 3, or 4 if the (M/L) ratios are included. This is exactly as expected for a manifold of King (1966) models.

Constraining the input parameter set to either core or half-light ones, brings the statistical dimension of the data set to 2, i.e., the triplets of observables are connected by bivariate correlations (Djorgovski 1995; see Fig. 2). This is the

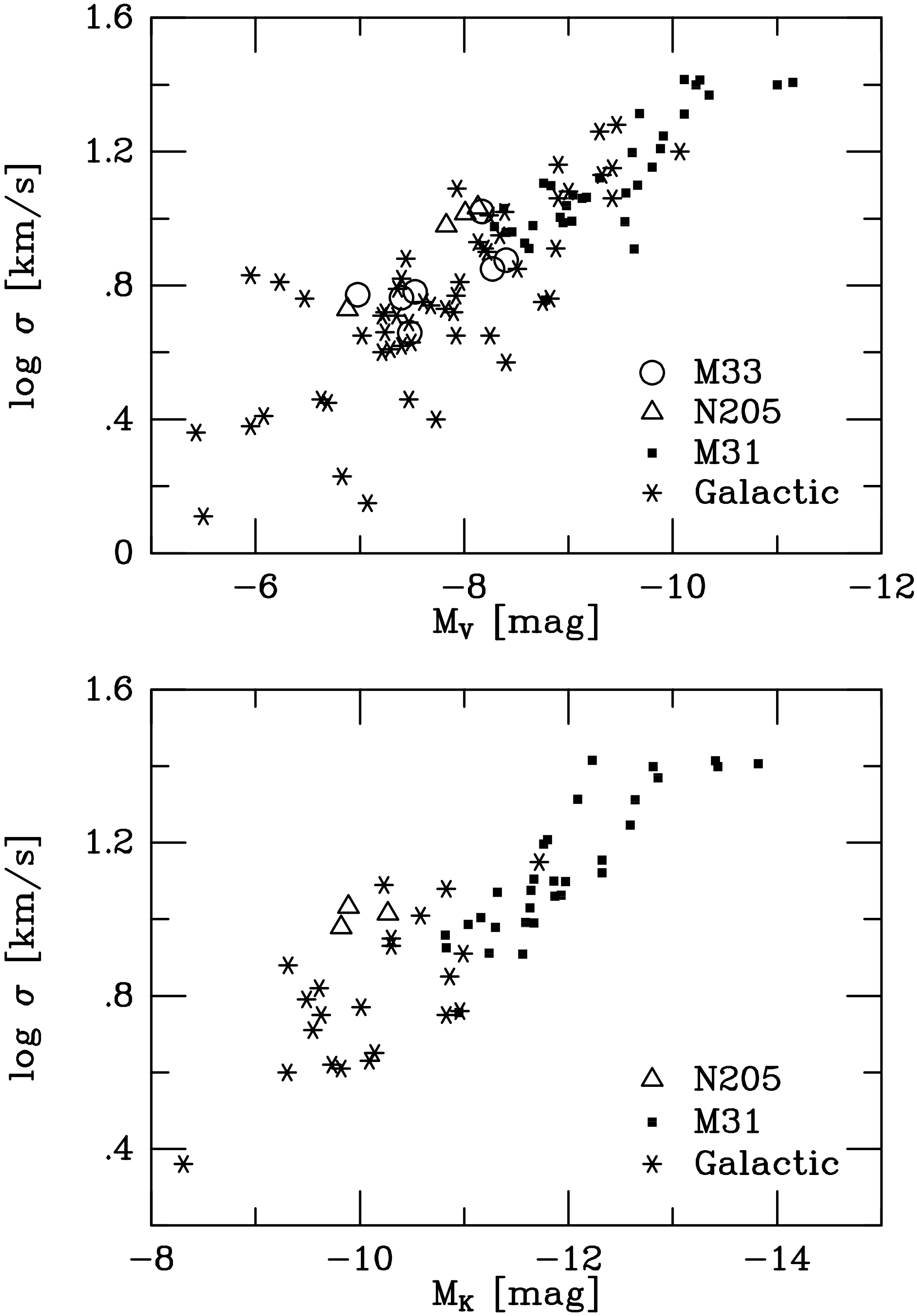

Figure 3. Luminosity – velocity dispersion correlations in the V (top) and K (bottom) bands for GCs in 4 Local Group galaxies, encoded with different symbols as indicated in the figure. The clusters in N205 appear to be slightly underluminous for their velocity dispersions, but this may be due to a systematic error. Otherwise, all of these GC systems appear to follow the same dynamical correlations.

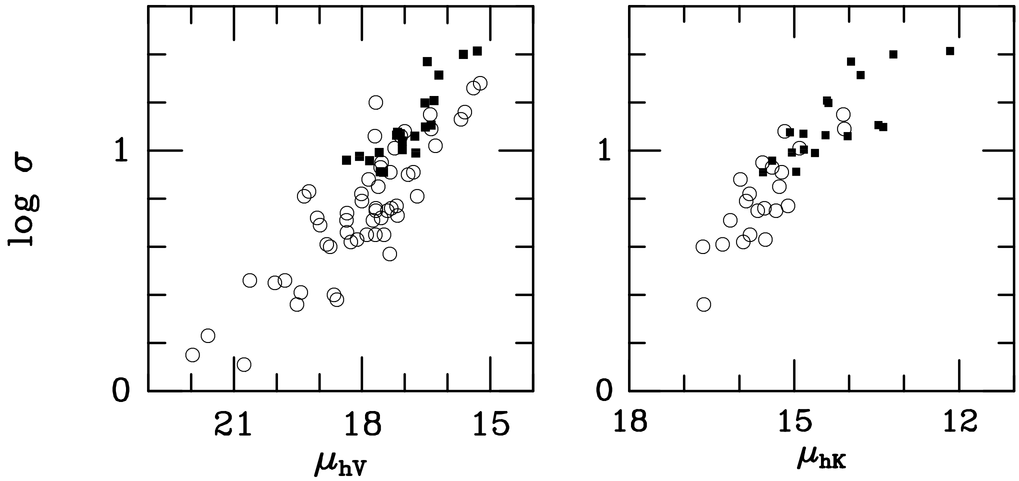

Figure 4. Correlations between the velocity dispersion σ and the mean surface brightness within the half-light radius in the V band (μ_{hV}, left panel) and in the K band (μ_{hK}, right panel) for the Galactic GCs (open circles) and M31 GCs (solid squares). The M31 extends to higher luminosities and masses, and is selection-limited at the low end, but in the overlap region the two GC systems follow the same correlations.

equivalent of the Fundamental Plane (FP) of elliptical galaxies. For the core parameters, the scaling relation is: $r_c \sim \sigma^{2.0\pm0.2} I_0^{-1.1\pm0.1}$. If we assume a structural homology (probably a good assumption for the GC cores), the virial theorem implies: $r \sim \sigma^2 I^{-1} (M/L)^{-1}$. Thus, the FP of GC cores implies that their (M/L) ratios are (nearly?) constant; this is the *sharpest* observational constraint on the constancy of GC (M/L) ratios to date. In contrast, for the half-light parameters, the scaling relation is: $r_h \sim \sigma^{1.45\pm0.2} I_h^{-0.85\pm0.1}$. This is remarkably similar to the FP of E-galaxies, and is almost certainly a consequence of the non-homology of GC structures.

An alternative look at the FP of GCs was provied by McLaughlin (2000). While recognizing the equivalence of his FP with the one described above, his prefered scaling relation is the expression of the binding energy, $E_b \sim L^{2.05} R_{GC}^{-0.4}$, where the 2nd term effectively corrects for the known dependences of the GC parameters on their position in the Galaxy. However, we note that the binding energy can be written as: $E_b = L^2 (M/L)^2 r_h^{-1} f(c)$, where $f(c)$ is a slow function of the cluster concentration. If the (M/L) ratios are indeed constant, and knowing that r_h does not correlate much with anything, it is then not surprising that the observed, R_{GC}-corrected scaling is $E_b \sim L^{2.05}$.

3. A Comparison of Dynamical Correlations for GCs in Five Local Group Galaxies: Some Preliminary Results

Correlations between the velocity dispersion and other parameters (L, I_0, I_h, and the FP) may probe directly the physics and formative processes of GCs, their

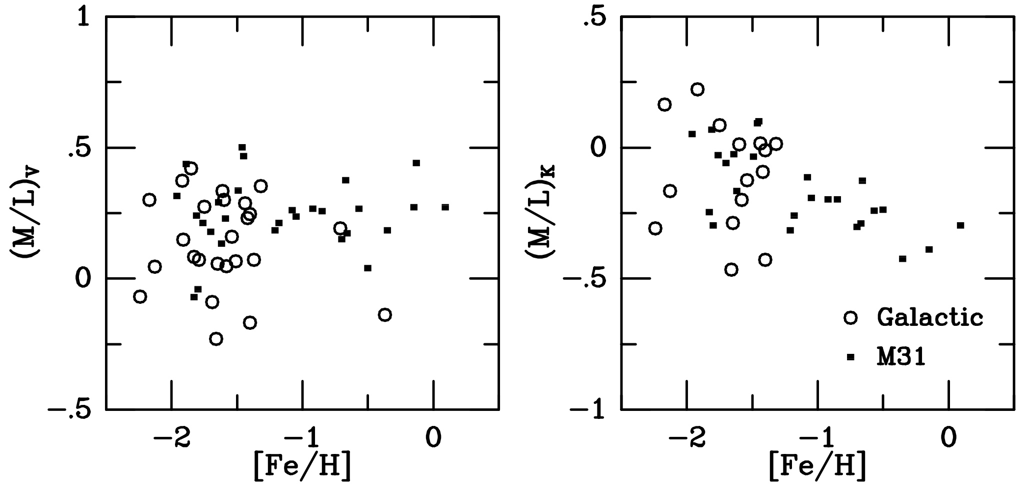

Figure 5. Dependence of the derived (M/L) ratios (in Solar V band units) on the metallicity, for the Galactic GCs (open circles) and M31 GCs (solid squares), in the V (left) and K (right) bands. The larger observed scatter for the Galactic GCs may be caused in part by the distance errors, whereas all M31 GCs are effectively at the same distance. While no trend is seen in the V band (as implied by the FP; see above), there is a trend in the K band in the sense of more metal-rich clusters having more luminous stellar populations at a given mass.

homogeneity (or lack thereof) in different galaxies, and can be also used as new distance indicator relations for their parent galaxies, providing an independent check of other distance scales. Fusi Pecci et al. (1994) and Barmby et al. (2002) established that the structural and photometric parameters of GCs in M31 as observed with the HST occupy the same portion of the parameter space as the Milky Way GCs. Following on the initial studies by Dubath & Grillmair (1997) and Djorgovski et al. (1997), we set to explore in more detail the dynamical correlations for GCs in 5 Local Group galaxies: the Milky Way, M31, M33, N185, and N205.

The extra-Galactic sample consists of HST imaging of GCs in M31, M33, N185, and N205 available as of the early 2002, for which we have done surface photometry (Federici, Parmeggiani, et al., in prep.). Velocity dispersions have been measured using Echelle spectra obtained at the Keck-I telescope with the HIRES instrument, as described, e.g., in Djorgovski et al. (1997); these measurements will be presented in detail elsewhere (Côté et al., in prep.).

Figures 3–5 illustrate some of our preliminary results. Our first conclusion is that GCs in these different galaxies follow essentially the same dynamical correlations. This suggests a common set of physical mechanisms affecting their formation and evolution, despite a broad range of their host galaxy properties. The observed dependence of the (M/L) ratios on the metallicity, especially in the K-band (Fig. 5), represents a useful observational constraint on the models of old stellar populations. In a future paper (Djorgovski et al., in prep.) we will present a more complete and detailed analysis, including the FP correlations for these GC systems.

Even with the resolution of the HST, such studies cannot be pushed much beyond the Local Group. For example, Harris et al. (2002) present an excellent study of GCs in Cen A = N5128.

Acknowledgments. We wish to thank our collaborators, and the staff of W.M. Keck Observatory for their expert help during our observing runs. This work was supported by grants from the NSF, NASA/STScI (GO-6671 and AR-8735), and private donors in the U.S., and ASI and MURST in Italy. PC was supported in part by a Fairchild Fellowship, and TJ by a SURF Fellowship at Caltech.

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